

Large amplitude variability from the persistent ultracompact X-ray binary in NGC 1851

Thomas J. Maccarone

School of Physics and Astronomy, University of Southampton, Hampshire SO17 1BJ, United Kingdom

Knox S. Long

Space Telescope Science Institute, Baltimore MD 21218, USA

Christian Knigge, Andrea Dieball

School of Physics and Astronomy, University of Southampton, Hampshire SO17 1BJ, United Kingdom

David R. Zurek

Department of Astrophysics, American Museum of Natural History, New York NY 10024, USA

ABSTRACT

Using archival RXTE data, we show that the ultracompact X-ray binary in NGC 1851 exhibits large amplitude X-ray flux variations of more than a factor of 10 on timescales of days to weeks and undergoes sustained periods of months where the time-averaged luminosity varies by factors of two. Variations of this magnitude and timescale have not been reported previously in other ultracompact X-ray binaries. Mass transfer in ultracompact binaries is thought to be driven by gravitational radiation and the predicted transfer rates are so high that the disks of ultracompact binaries with orbits as short as that of this object should not be susceptible to ionization instabilities. Therefore the variability characteristics we observe were unexpected, and need to be understood. We briefly discuss a few alternatives for producing the observed variations in light of the fact that the viscous timescale of the disk is of order a week, comparable to the shorter time scale variation that is observed but much less than the longer term variation. We also discuss the implications for interpretation of observations of extragalactic binaries if the type of variability seen in the source in NGC 1851 is typical.

Key words: accretion, accretion discs – X-rays:binaries – X-rays:individual:4U 0513-40 – globular clusters: individual: NGC 1851

1 INTRODUCTION

Ultracompact X-ray binaries are semi-detached binary star systems in which a neutron star or a black hole accretes material from a Roche-lobe overflowing white dwarf. They are of astrophysical interest for a variety of reasons. It is expected that some ultracompact X-ray binaries should be detectable as gravitational wave sources with missions like LISA (see e.g. Benacquista 1999). Additionally, they present an opportunity to study plasma astrophysics in hydrogen-free gas, where the mass-to-charge ratio is different than in most other astrophysical systems.

The most recent compilation of ultracompact X-ray binaries in the Galaxy contained 27 candidates (in 't Zand, Jonker & Markwardt 2007 – IZJM07). The most secure iden-

tifications of ultracompact X-ray binaries come through direct measurements of their orbital periods, ranging in the observed sample from 11 to 50 minutes (IZJM; Galloway et al. 2002; Middleditch et al. 1981; Markwardt et al. 2002, 2003; Stella et al. 1987; Homer et al. 1996; White & Swank 1982; Dieball et al. 2005; and Zurek et al. 2009 for the period measurement of the object discussed in this paper). At the time of publication of IZJM07, only 7 had well-estimated orbital periods. The remainder were classified as ultracompact X-ray binaries on the bases of some combination of tentative orbital period measurements, deep optical spectra lacking hydrogen emission lines, high ratios of X-ray to optical flux, or persistent emission at low fractions of the Eddington rate (IZJM07 and references within). The persistent ultracom-

compact X-ray binaries typically have X-ray luminosities from about $10^{36} - 10^{37}$ ergs/sec.

Understanding the formation mechanisms for ultracompact X-ray binaries is also of great interest. The shortest period ultracompact X-ray binaries (i.e. those with orbital periods less than 30 minutes), for example, are predominantly in globular clusters (see e.g. the tabulation in IZJM07), and thus their production may be dominated by mechanisms which are inherently stellar dynamical, such as direct collisions between neutron stars and red giants (e.g. Verbunt 1987). However, theoretical work does suggest that it is possible to form white dwarf-neutron star binaries with orbital periods less than 30 minutes by going through an intermediate phase where the donor star is a helium star (e.g. Savonije, de Kool & van den Heuvel 1986). At least the shortest period ultracompact binaries are relatively easy to detect, as they are bright ($L_X \gtrsim 10^{36}$ ergs/sec), persistent X-ray emitters. These thus represent samples of double degenerate stars with relatively well understood selection effects, and which can be seen nearly throughout the Galaxy. Other classes of binary compact objects which are of great astrophysical interest include double white dwarfs, which may be the progenitors of Type Ia supernovae (Iben & Tutukov 1984) and double neutron stars, which are showing increasingly strong evidence for being the progenitors of short-hard gamma-ray bursts (e.g. Bloom et al. 2006).

Understanding the evolution of double compact binaries is likely to require using multiple source classes to gather constraints. Double neutron stars, for example, are both rare, and very difficult to detect. Mass transferring double white dwarf systems can be studied in great deal once they are detected (e.g. Roelofs et al. 2007), but their sample sizes are only slightly larger than those for the ultracompact X-ray binaries, and the relative robustness to selection effects in surveys of neutron star ultracompact X-ray binaries and mass transferring double white dwarf systems is not yet clear.

In the absence of orbital period estimates, candidate ultracompact X-ray binaries can be found through measurements of large X-ray to optical flux ratios (e.g. Juett et al. 2001). This signature is expected for short orbital period systems since the optical emission from most bright X-ray binaries is dominated by reprocessing of X-rays in the outer accretion disk, leading to a correlation between X-ray to optical flux ratio and orbital period (van Paradijs & McClinck 1994). Additional candidate UCXBs can be identified from strong upper limits on hydrogen emission lines in optical spectra (e.g. Nelemans et al. 2004), or by detection of persistent bright hard X-ray emission combined with low rates of Type I X-ray bursts (IZJM07).

Bildsten & Deloye (2004) have suggested that ultracompact X-ray binaries may be the dominant population in elliptical galaxies. The typical X-ray luminosity functions seen in elliptical galaxies (e.g. Kundu et al. 2002; Kim & Fabiano 2004; Gilfanov 2004), and the similarities between the luminosity functions of globular cluster X-ray sources and non-cluster X-ray sources in the elliptical galaxies (Kundu et al. 2002) are a major part of the evidence they suggest for this idea. The elliptical galaxy X-ray observations used in this analysis typically consist of snapshots of about half a day. Strong variability can cause the observed luminosity functions in snapshots to be different from the luminosity

function which would be obtained when averaging over long durations.

In this paper, we present the X-ray light curve of 4U 0513-40 from RXTE pointed observations. This X-ray binary, in the Galactic globular cluster NGC 1851, has a 17-minute orbital period – short enough that irradiated disc models (Lasota et al. 2008) predict it should not be subject to the standard ionisation instability (i.e. it should always be sufficiently ionised to exist in the high viscosity state), and hence should persistently be a bright X-ray source. It *is* persistent in the sense that it is always detectable above L_X of about 10^{36} ergs/second. However, we also present evidence for variability of a factor of ~ 10 in X-ray luminosity on timescales of \sim weeks, and a factor of more than 20 overall. Such variability is unusual for ultracompact X-ray binaries, and contrary to the expectations from ionisation instability theory for such source. 4U 0513-40 also shows variations at the factor of 2 level in the time averaged luminosity over years, with no strong indications of any periodicities in the long term light curve.

2 DATA USED, ANALYSIS PROCEDURE, AND RESULTS

We have analyzed the archival RXTE data for 4U 0513-40. We use all data from proposals P10078, P30407, P40404, P50403, P60406, P70403, P90402, P91402, P92403 and P93403, which include a total of 740 observations made between March 1996 and December 2008. We take the standard product light curves over the channels from 2-9 keV. The data have been filtered by the RXTE PCA team using the standard criteria (a pointing offset less than 0.02 degrees from the target position and an Earth elevation of at least 10 degrees). All proportional counter units with at least 95% as much time turned on as the counter with the largest “on time” are included. The faint source models are used for background subtraction in cases where the count rate is less than 64 counts/sec/per PCU, which includes nearly all of the observations of NGC 1851. After background subtraction, light curves are produced in counts/sec/PCU.

We then re-bin the standard products data from 16 seconds to 1024 seconds, using the *lcurve* task in XRONOS, so that there will typically be 2-4 data points per observation. This rebinning yields a manageable total number of time bins in a single light curve containing all data points for NGC 1851. The count rates as a function of time are presented in Figure 1, while in Figure 2, we zoom in on a representative few months of the light curve, and in Figure 3, we zoom in on an atypical portion of the light curve where the count rate and amplitude of variability are smaller than typical.

In order to ensure that the relationship between the count rate and the luminosity does not change strongly as a function of the spectral state of the system, we have extracted spectra of two observations – one which is among the highest count rate observations and one which is among the lowest count rate observations. The low count rate observation, which has RXTE observation identification number 93403-01-13-02, was made on 19 October 2007. Its X-ray spectrum is well modelled by a $\Gamma = 2.2$ power law, with the Galactic absorption column density of $4.4 \times 10^{20} \text{ cm}^{-2}$,

and with no evidence for a strong thermal component. The higher count rate observation, which has RXTE observation identification number 93403-01-48-04, and which was made on 22 December 2008, is well fit by Galactic absorption plus a 2.3 keV blackbody component which contains most of the flux, and a $\Gamma = 2.8$ power law tail. The former observation has a count rate of 7.2 counts per second per proportional counter unit (PCU), while the latter has a count rate of 50.1 counts per second per PCU, in both cases from 2-20 keV. The former observation has a flux of 9.8×10^{-11} ergs/sec/cm², while the latter has a flux of 6.7×10^{-10} ergs/sec/cm². The ratio of count rate to flux varies by only about 5% between these two observations, so, given that the count rate varies by a factor of more than 10, the use of the count rate to trace the luminosity is well justified. In both cases, about 20% of the source counts come from 9.0-20.0 keV, so the 2-9 keV count rates also are well representative of the bolometric luminosity; the X-ray spectral differences are largely reflected only in the high energy tail of the spectrum, significant changes in the best fitting spectral model can occur with only small changes in the bolometric luminosity to count rate ratio.

As an additional test of whether the count rate is a good tracer of bolometric luminosity, we compute hardness ratios for 4U 0513-40 over the full set of observations studied here, dividing the count rate from 4-9 keV by the count rate from 2-4 keV. These are plotted in Figure 4. The variations in hardness are smaller than the measurement errors on the hardness. We note that the observations made in 1996 do have a different hardness ratio than the rest of the data, but we also note that the RXTE gain was changed shortly after those data were taken, moving the lower energy threshold for photon detection substantially.¹ The ratio of Counts(9-20 keV)/Counts(4-9 keV) shown in Figure 5 is less susceptible to this gain change and is consistent with being constant even across the 1996-1998 time gap.

The X-ray flux of 4U 0513-40 varies from about 9×10^{-11} ergs/sec/cm² (about 20 times the RXTE confusion limit – Jahoda et al. 2006) to about 2×10^{-9} ergs/sec/cm². Assuming a distance of 12 kpc (Alcaino 1976), this corresponds to a luminosity variation from about 1.4×10^{36} to 3×10^{37} ergs/sec. This is in agreement with the fact that the spectral state of this system appears to be banana-like (i.e. occupying a particular region in a colour-colour diagram that looks like a banana, and which is characterized by being dominated by a quasi-thermal spectrum – Hasinger & van der Klis 1989) at its brightest, and island-like (occupying a region in the X-ray colour-colour diagrams of Hasinger & van der Klis 1989 that looks like an island, and which is characterized by relatively strong non-thermal emission) at its faintest. Therefore, the source makes a spectral state transition near the bottom of its luminosity range, in the few per cent of Eddington luminosity range where X-ray binaries normally make spectral state transitions (Maccarone 2003). The mean X-ray luminosity of 4U 0513-40 is about 3×10^{36} ergs/sec and the mean accretion rate is then about 3×10^{16} g/s, assuming $L_X = 0.1 \dot{m} c^2$. Theoretical tracks of mass accretion rate versus orbital period predict accretion

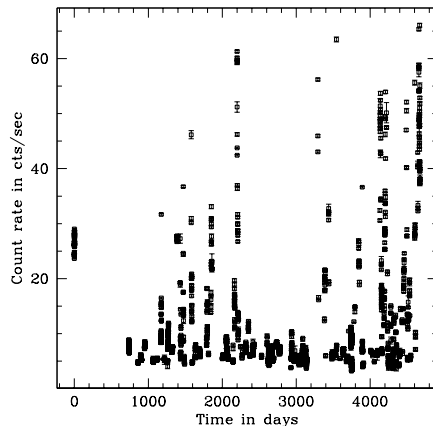


Figure 1. The full RXTE lightcurve for 4U 0513-40. The x-axis gives the time in units of days beginning from the start of the first observation of the source, which occurred at 3:58:24 UT on 7 March 1996. The y-axis shows the count rate in counts per second, from 2-9 keV.

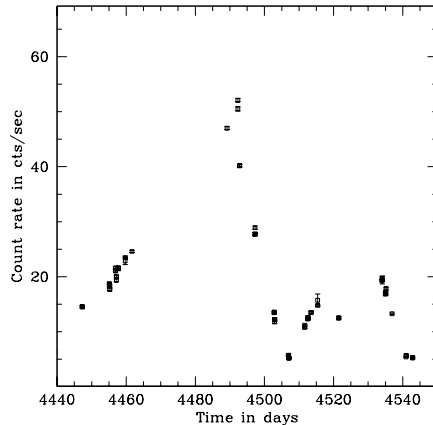


Figure 2. The RXTE lightcurve for 4U 0513-40, from days 4450 to 4550 (i.e. starting from 13 May 2008). The units on the axes are the same as for figure 1. The figure shows a typical large amplitude change in the intensity of the source, which is of a factor of more than 10 in count rate, and takes place on a timescale of a few weeks.

rates of 4×10^{16} g/sec (to within a factor of 2) for an ultra-compact X-ray binary with an orbital period of 17 minutes (Deloye & Bildsten 2003). The theoretical uncertainty of a factor of 2 is determined primarily by the chemical composition of the white dwarf (with higher mass transfer rates expected from pure He white dwarfs than white dwarfs rich in carbon and/or oxygen), but the initial temperature of the white dwarf also can play a role, with hotter white dwarfs transferring mass more quickly.

From the light curve plots, it is clear that 4U 0513-40 varies in count rate by a factor of about 10. One can then compare this variation with those of more nearby persistent neutron star X-ray binaries and find that this is a much larger amplitude of variability than is typical. The two most well-known Z-sources, Cygnus X-2 and Scorpius X-1, vary by factors of about 3 in the dwell-

¹ The RXTE gain epochs are documented at <http://heasarc.gsfc.nasa.gov/docs/xte/e-c.table.html>.

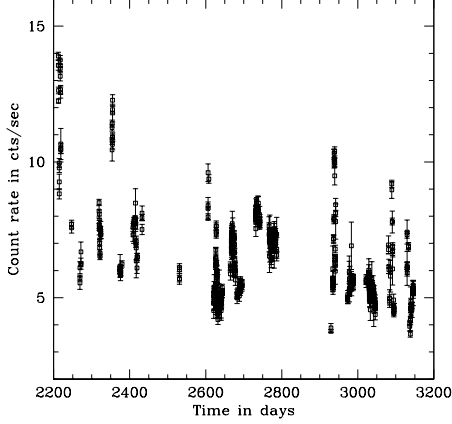


Figure 3. The RXTE lightcurve for NGC 1851, from days 2200 to 3200 (i.e. from 27 March 2002 through 11 December 2004). The units on the axes are the same as for figure 1. The amplitude of variations from 4U 0513-40 over the middle of this time span is considerably smaller than over the spans before and after.

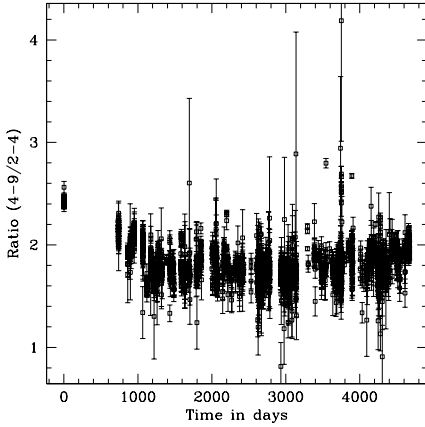


Figure 4. RXTE colours for NGC 1851. The data presented are the ratio of counts from 4-9 keV to the counts from 2-4 keV. We note that while it appears the hardness has changed substantially between the first few points and the first few data points are from the short-lived first RXTE gain epoch, while the remainder are all from epochs 3-5. The largest change in the RXTE lower energy threshold came between epochs 2 and 3.

by-dwell light curve plots from the RXTE All-Sky Monitor (http://xte.mit.edu/ASM_lc.html, accessed 2 February 2010). The two systems which are classified as *atoll* sources in the catalog of Liu et al. (2001), and which are confirmed to be ultracompact X-ray binaries, 4U 1820-303 and 4U 0614+091, both vary by factors of less than 3 over the ASM light curves. There is at least one neutron star source which shows stronger variability without ever going into quiescence – 4U 1705-440 which varies by a factor of about 60 (see e.g. Homan et al. 2009), but this system’s orbital period is not known. It thus appears likely that the level of variability seen from 4U 0513-40 is unusual for an ultracompact X-ray binary. On the other hand, the variations seen from 4U 0513-40 are considerably less than the factors of 10^4 or more in variability seen from bona fide transients.

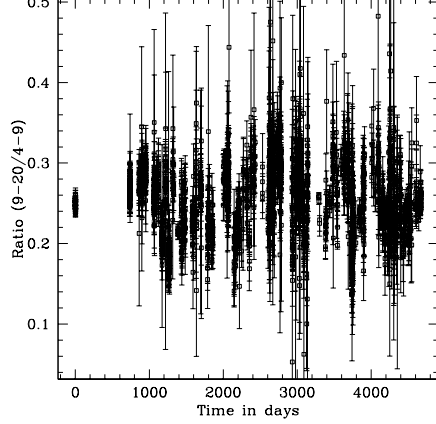


Figure 5. RXTE colours for NGC 1851. The data presented are the ratio of counts from 9-20 keV to the counts from 4-9 keV.

The time sampling of 4U 0513-40 is insufficiently uniform for making a reliable power spectrum without detailed simulations. Nonetheless, simple inspection of the light curve indicates strong variability on a variety of timescales. A series of sharp rises in the intensity are seen from day 1400-2200 and from day 3400 to the end of the light curve. An epoch folding search for periodicities in the light curve indicates marginal evidence for periodicity at about 88 days, but only when rather long phase bins are used (1/8 or 1/16 of the period). This is most likely due to this timescale being close to the spacings of a few of the sharp increases in intensity, and is thus likely to be spurious. The period is not detected when finer bins are used for the folding. Indeed, it is clear from simple inspection of the light curve between days 2400 and 3200, where the count rate never rises above about 10 counts per second, that the light curve cannot be described adequately as simply a periodic variation on a ~ 90 day timescale.

We also looked for rapid variability within several individual observations, but found that the source power spectra were generally dominated by Poisson noise. This was not surprising – the source spends most of its time at luminosities high enough that we expect it to be in a “banana” state, where the integrated fractional rms amplitude of variability should be only a few percent (see e.g. Berger & van der Klis 1998). In the “island states”, where the rms fractional amplitude can approach 30% (see again, for example, Berger & van der Klis 1998), the count rate will typically be only about 30 counts per second (for the rare observations where all PCUs are on), and the background rate will be a substantial fraction of the total count rate. Additionally, the power is dominated by variability at ~ 10 Hz in these states, so that more Poisson noise must be integrated up to try to detect variability. As a double-check on the feasibility of detecting rapid variability, we can apply $n_\sigma = \frac{1}{2} I r^2 \left(\frac{T}{\Delta\nu} \right)^{\frac{1}{2}}$ from van der Klis (1989), which gives the signal to noise n_σ in terms of the count rate I , fractional rms amplitude r , exposure time T , and frequency width $\Delta\nu$. Typical values in a banana state are $\Delta\nu = 1$ Hz, $I = 200$ counts/sec (assuming 5 PCUs), $r=0.03$ and $T=3000$ seconds, yielding a signal to noise of 2.5, while in an island state, $\Delta\nu = 10$ Hz, $I = 30$ counts/sec (assuming 5 PCUs), $r=0.15$ (30% rms amplitude,

but with only half the counts from the source) and $T=3000$ seconds, yielding a signal-to-noise of about 6 – large enough to make a detection of variability, but not large enough to use power spectral analysis to help understand the source.

2.1 Long timescale variability

There are no strong luminosity flares observed between June 2002 and March 2005 – days 2300 through 3200 from the first observation in the series. This section of the light curve is plotted in Figure 3. The mean count rate is 6.33 ± 0.07 counts/sec during the low flux epoch, and 12.7 ± 0.3 during the rest of the light curve. Comparing the distribution of count rates during this epoch with the distribution over the rest of the light curve using a Kolmogorov-Smirnov test yields a probability of 1.6×10^{-58} that the same underlying count rate distribution could produce these two epochs. Therefore, the data from the low count rate epoch could not have resulted from uncorrelated fluctuations in the count rates and hence reveal a real physical change in the source.

3 DISCUSSION

The variability from 4U 0513-40 has two important characteristics. The first is that it is that the source manages to exhibit large amplitude X-ray variability, while remaining persistently bright – well above the $\sim 10^{32}$ ergs/sec level at which crustal emission from the neutron star, rather than accretion is the dominant source of X-rays (e.g. Wijnands et al. 2001). The second is that the time averaged luminosity varies even if one averages over timescales as long as a few years (see e.g. the lack of any strong flares between days 2400 and 3200). Since such timescales are far longer than any reasonable propagation timescale through a disc of such small radius, this suggests real deviations of the mass transfer rate from that predicted due to gravitational radiation, or at least some sort of disc instability with a characteristic timescale far longer than the viscous timescale.

Several classes of mass transferring binaries are at short enough orbital periods that gravitational radiation is expected to dominate over magnetic braking as the process responsible for the systems' orbital evolution. It has long been known that, in some cases where the donor stars are non-degenerate, the mass transfer rates can exceed the mass transfer rates predicted from gravitational radiation alone (e.g. Osaki 1995). However, the systems where strong deviations from the expectations due to gravitational radiation have previously been reported all had low mass main sequence donor stars, which are like to be more susceptible to stellar atmospheric effects which could change the accretion rate than are white dwarf stars. Among both the ultracompact X-ray binaries and the AM CVn stars (mass transferring double white dwarfs), the persistent systems have shown mass transfer rates consistent with the predictions from gravitational radiation (Deloye & Bildsten 2003; Roelofs et al. 2007), without any reported evidence for large amplitude variability (albeit with small samples of objects, most of which have not been monitored intensively). Cataclysmic variables with main sequence/subgiant donor stars have in many instances shown evidence for deviations of the

accretion rates from secular values on a range of timescales (e.g. Townsley & Gaensicke 2009).

3.1 Possible causes

The viscous timescale of an accretion disc is given by:

$$t_{\text{visc}} = 2 \times 10^6 \text{sec} (\alpha/0.1)^{-4/5} \dot{M}_{16}^{-3/10} M_1^{1/4} R_{10}^{5/4}. \quad (1)$$

Here, α is the dimensionless viscosity parameter, \dot{M}_{16} is the mass accretion rates in units of 10^{16} g/sec, M_1 is the mass of the accretor in solar masses, and R_{10} is the radius from which the viscous timescale is being computed in units of 10^{10} cm (Frank, King & Raine 1995). For 4U 0513-40, using $\dot{m} \sim 3 \times 10^{17}$ g/sec as appropriate to the hot state for the disk, $t_{\text{visc}} \sim 10(\alpha/0.1)^{-4/5}$ days. This timescale agrees reasonably well with the durations of the increases in luminosity seen from this system.

Given the reasonable (i.e. within factors of a few) agreement between flaring timescales and the disc's viscous timescale, it is worth considering whether we may be seeing a weak disc instability. Considerable work has been done to estimate the accretion rates at which discs are susceptible to ionization instabilities. The lowest observed luminosities from this system are at about 10^{36} ergs/sec, which corresponds to 1.1×10^{16} g/sec if $L_X = 0.1 \dot{m} c^2$ as is typically assumed for neutron stars. Menou et al. (2002) presented the first calculation of the critical accretion rates for hydrogen-poor discs, and found that for an orbital period of 17 minutes, the critical accretion rate would be about 1×10^{16} g/s for discs with substantial carbon content, and about 5×10^{16} g/s for discs made of either pure helium or pure oxygen. Lasota et al. (2008) showed that irradiation of the outer disc by the X-rays produced in the inner disc, which were ignored in the work of Menou et al. (2002) reduce the stability threshold for \dot{m} by a factor of about 4. Thus while the accretion rate is close to the threshold for stability in the state-of-the-art calculations of the disc instability model for hydrogen-poor gas, it is unlikely that classical ionization instabilities are the proper explanation for what we observe here. Additionally, in at least some of the flaring events, the rise times are slower than the decay times, something which is not typical of ionization instability driven outbursts.

The long timescale variations seen seem to imply that the actual mass transfer rate from the white dwarf to the outer disk of the neutron star is varying on a timescale of order a year. As noted above, data to date on mass transferring binaries with white dwarf donors has found all are consistent with the mass transfer rates expected from evolution driven purely by gravitational radiation, apart from the known 179 day periodicity in the light curve of 4U 1820-30 (whose mean luminosity agrees well with gravitational radiation predictions). The mean luminosity for 4U 0513-40 agrees, within the errors, with that predicted based on the system's orbital period and the assumption that the accretor is a $1.4 M_\odot$ neutron star (see e.g. Deloye & Bildsten 2003 for predictions of X-ray luminosities based on realistic models of white dwarf donors), but the aperiodic variations in the accretion rate on long timescales suggest that real variations are taking place in the accretion rate on these timescales.

A variety of mechanisms have been proposed for causing accretion rates to vary from those expected based on

the orbital and stellar parameters in a binary system. These include small orbital eccentricities (e.g. Hut & Paczynski 1984), perhaps due to the presence of a third body in the system (Kozai 1962; Zdziarski et al. 2007); tidal disc instabilities (e.g. Whitehurst 1988; Osaki 1995); star-spot blocking of the inner Lagrange point (e.g. Livio & Pringle 1994) and irradiation of the donor star leading to modulations of \dot{m} (e.g. Hameury, King & Lasota 1986). It is not clear whether any of these mechanisms can explain either the short term flaring or longer timescale variability we report here. Also, the lack of days to weeks variability in 4U 1820-30 and in the other well-sampled ultracompact X-ray binary, 4U 1543-64 (Schultz 2003), imply that whatever mechanism is at work for explaining the flaring behaviour in 4U 0513-40 cannot generically apply to all ultracompact X-ray binaries.

Most of the models above do not make specific predictions for how variability would manifest itself in accreting neutron star systems. However, a few statements can be made about the relative likelihoods of the above mechanisms. White dwarfs are not thought to have convective regions, and hence the star spot model is not likely to be relevant for these data. The Kozai mechanism predicts strictly periodic variations, rather than the aperiodic variability we see here. One could, in principle, involve a fourth body, in which case chaotic behavior might be seen, but the probability of such a system being formed is likely to be small. Additionally, the outer bodies would have to be quite faint, in order not to dominate the optical flux from the system.

The two other mechanisms, tidal instabilities and irradiation driven mass transfer instabilities remain viable. The chief criterion required for tidal instabilities to be a possibility is to have large mass ratio in the binary system (e.g. Whitehurst 1988; Osaki 1995), in agreement with what is seen here. Irradiation induced mass transfer cycles involve nonlinear feedback and have not been studied in detail in the context of systems with white dwarf donor stars, so it is difficult to make any specific statements about their viability for explaining what we have observed. Nonetheless, it is worth noting that the original motivation for our investigation of the long term variations of the X-ray luminosity in this system came from the variations in the rms amplitude of the periodic signal in the ultraviolet emission we used to find this system's orbital period (Zurek et al. 2009). We thus already found that it is likely that the white dwarf in this system undergoes sufficient irradiation to lead to a measurable difference in temperatures of its heated and unheated faces, and that the extent to which the temperature varies across the white dwarf's surface varies with time. Irradiation induced mass transfer cycles are then feasible, provided one can find a mechanism by which they are seen prominently in 4U 0513-40, but are not seen prominently in the brighter, tighter binary system 4U 1820-30.

3.2 Implications for studies of extragalactic X-ray binaries

The surprising results shown here may have important implications for interpretations of data on extragalactic X-ray binaries. Bildsten & Deloye (2004), for example, have suggested that most of the X-ray binaries seen in elliptical galaxies are ultracompact X-ray binaries, with the strongest piece of evidence in favor of this claim being the similarity

of the luminosity function predicted for ultracompact X-ray binaries to that observed in the elliptical galaxies. However, the observations considered by Bildsten & Deloye (2004) are predominantly ~ 40 kilosecond observations of galaxies at distances of $\approx 10 - 20$ Mpc. A system with the same systems parameters 4U 0513-40, placed at such distances could be detectable only in its brightest epochs. However, shorter period systems could be expected to be detected most of the time. Finding large amplitude variability to be common in ultracompact X-ray binaries would then imply that snapshot X-ray luminosity functions of elliptical galaxies are not reliable tracers of the time-averaged mass transfer rate distributions even for "simple" X-ray binary systems like ultracompacts.

Additionally, large monitoring campaigns of elliptical galaxies have recently begun to be undertaken such as the *Chandra* Very Large Programs on the galaxies NGC 3379 and NGC 4278 (e.g. Brassington et al. 2008, 2009). In these campaigns, the criterion for calling a source a transient has been variability at the factor of 10 level. However, the observations presented here show that variability at more than the factor of 10 level is possible in sources that are expected to be persistently accreting at high rates, and indeed, found to be persistently accreting at high rates over timescales of at least a decade. As a result, if systems such as 4U 0513-40 are common, there may be many objects classified as transients which are actually persistent sources with large variability amplitudes. A common assumption is that the brightest (and hence shortest period) ultracompact X-ray binaries will be steady sources, so the finding that short period ultracompact X-ray binaries can be so strongly variable should have important implications for such work. At the present time, it remains to be seen whether 4U 0513-40 is peculiar among the persistent ultracompact X-ray binaries, or part of a relatively common subset of sources; the combination of good sampling in time with good sensitivity that could be provided by proposed all-sky X-ray observatories such as LOBSTER (Fraser et al. 2002) would be able to help answer this question.

4 CONCLUSIONS

The ultracompact X-ray binary 4U 0513-40 in the globular cluster NGC 1851 shows large amplitude variability on a variety of timescales. Of particular interest are the variations of factors of ~ 10 on timescales of several weeks and the variations in the luminosity when time averaged over ~ 1 year. While it may be possible to explain the \sim weeks timescale variability through tidal instabilities in the accretion disc, the latter almost certainly must be explained in terms of modulation of the actual accretion rate. Given that this system's evolution is thought to be driven primarily by gravitational radiation, and that the mean luminosity agrees well with that scenario, the finding of significant deviations from a constant mass transfer rate is interesting, and needs to be explained.

ACKNOWLEDGMENTS

We thank Phil Uttley for discussions about statistics. We thank the first referee Jean-Pierre Lasota for useful comments regarding irradiated discs, and an anonymous second referee for several constructive comments which improved this paper. KSL and DRZ were supported by NASA through grant GO-10184 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA grant NAS5-26555. This work makes use of results provided by the ASM/RXTE teams at MIT and at the RXTE SOF and GOF at NASA's GSFC.

REFERENCES

- Alcaino G., 1976, *A&A*, 50, 299
- Benacquista M., 1999, *ApJ*, 520, 233
- Berger M., van der Klis M., 1998, *A&A*, 340, 143
- Bildsten L., Deloye C., 2004, *ApJL*, 607, 119
- Bloom J.S., et al., 2006, *ApJ*, 638, 354
- Brassington N.J., et al., 2008, *ApJS*, 179, 142
- Brassington N.J., et al., 2009, *ApJS*, 181, 605
- Deloye C.J., Bildsten L., 2003, *ApJ*, 598, 1217
- Dieball A., Knigge C., Zurek D.R., Shara M.M., Long K.S., Charles P.A., Hannikainen D.C., van Zyl L., 2005, *ApJ*, 634, L105
- Frank J., King A., Raine D., 1995, "Accretion power in astrophysics," Cambridge University Press: Cambridge
- Fraser G.W., et al., 2002, *SPIE*, 4497, 115
- Galloway D., Chakrabarty D., Morgan E.H., Remillard R.A., 2002, *ApJ*, 576, L137
- Gilfanov M., 2004, *MNRAS*, 349, 146
- Hameury J.-M., King A.R., Lasota J.-P., 1986, *A&A*, 162, 71
- Hasinger G., van der Klis M., 1989, *A&A*, 225, 79
- Homan J., Kaplan D.L., van den Berg M., Young A.J., 2009, *ApJ*, 692, 73
- Homer L., Charles P.A., Naylor T., van Paradijs J., Auriere M., Koch-Miramond L., 1996, *MNRAS*, 282, L37
- Hut P., Paczynski B., 1984, *ApJ*, 284, 675
- Iben I., Tutukov A.V., 1984, *ApJS*, 54, 335
- in 't Zand J.J.M., Jonker P.G., Markwardt C.B., 2007, *A&A*, 465, 593 (IZJM07)
- Jahoda K., Markwardt C.B., Radeva Y., Rots A.H., Stark M.J., Swank J.H., Strohmayer T.E., Zhang W., 2006, *ApJS*, 163, 401
- Juett A.M., Psaltis D., Chakrabarty D., 2001, *ApJ*, 560L, 59
- Kozai Y., 1962, *AJ*, 67, 591
- Kim D.-W., Fabbiano G., 2004, *ApJ*, 611, 846
- Kundu A., Maccarone T.J., Zepf S.E., 2002, *ApJ*, 574, L5
- Lasota J.-P., Dubus G., Kruk K., 2008, *A&A*, 486, 523
- Livio M., Pringle J.E., 1994, *ApJ*, 427, 956L
- Maccarone T.J., 2003, *A&A*, 409, 697
- Markwardt C.B., Swank J.H., Strohmayer T.E., in 't Zand J.J.M., Marshall F.E., 2002, *ApJ*, 575, L21
- Markwardt C.B., Juda M., Swank J.H., 2003, *ATel*, 127
- Menou K., Perna R., Hernquist L., 2002, *ApJ*, 564, L81
- Middleditch J., Mason K.O., Nelson J.E., White N.E., 1981, *ApJ*, 244, 1001
- Nelemans G., Jonker P.G., Marsh T.R., van der Klis M., 2004, *MNRAS*, 348L, 7
- Osaki Y., 1995, *PASJ*, 47, L11
- Roelofs G.H.A., Groot P.J., Benedict G.F., McArthur B.E., Steeghs D., Morales-Rueda L., Marsh T.R., Nelemans G., 2007, *ApJ*, 666, 1174
- Schultz J., 2003, *A&A*, 397, 249
- Stella L., Priedhorsky W., White N.E., 1987, *ApJ*, 312L, 17
- Townsley D.M., Gaensicke B.T., 2009, *ApJ*, 693, 1007
- van der Klis M., 1989, *ARA&A*, 27, 517
- van Paradijs J., McClintock J.E., 1994, *A&A*, 290, 133
- Verbunt F., 1987, *ApJ*, 312, L23
- Wang X., Chakrabarty D., 2009, astro-ph/0906.1984
- White N.E., Swank J.H., 1982, *ApJ*, 253, L61
- Whitehurst R., 1988, *MNRAS*, 232, 35
- Wijnands R., Miller J. M., Markwardt C., Lewin W. H. G., & van der Klis M. 2001, *ApJ*, 560, L159
- Zdziarski A.A., Wen L., Gierlinski M., 2007, *MNRAS*, 377, 1006
- Zurek D.R., Knigge C., Maccarone T.J., Dieball A., Long K.S., 2009, *ApJ*, 699, 1113